

# Forming Close-in Earth-like Planets via a Collision-Merger Mechanism in Late-stage Planet Formation

Jianghui Ji<sup>1,2</sup>, Sheng Jin<sup>1,3</sup>, C. G. Tinney<sup>2</sup>

## ABSTRACT

The large number of exoplanets found to orbit their host stars in very close orbits have significantly advanced our understanding of the planetary formation process. It is now widely accepted that such short-period planets cannot have formed *in situ*, but rather must have migrated to their current orbits from a formation location much farther from their host star. In the late stages of planetary formation, once the gas in the proto-planetary disk has dissipated and migration has halted, gas-giants orbiting in the inner disk regions will excite planetesimals and planetary embryos, resulting in an increased rate of orbital crossings and large impacts. We present the results of dynamical simulations for planetesimal evolution in this later stage of planet formation. We find that a mechanism is revealed by which the collision-merger of planetary embryos can kick terrestrial planets directly into orbits extremely close to their parent stars.

*Subject headings:* celestial mechanics – methods:numerical – planets and satellites:formation – stars:individual (OGLE-06-109L, 47 Ursae Majoris)

## 1. INTRODUCTION

To date over 490 extrasolar planets have been discovered, revealing a wide diversity of planetary systems (<http://exoplanet.eu>). One of more unusual phenomena so revealed has been the population of “Hot Jupiters” – gas-giants found in very small orbits (periods  $< 8\text{d}$ ) about their parent stars – of which the prototype was the very first gas-giant exoplanet discovered, 51 Peg (Mayor & Queloz 1995). It is believed that such short-period gas-giants cannot have formed this close to their parent stars, and so must have migrated in, or been scattered in, from a more distant formation region (Lin et al. 1996; Weidenschilling & Marzari 1996;

---

<sup>1</sup>Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China; jijh@pmo.ac.cn

<sup>2</sup>Department of Astrophysics, School of Physics, University of New South Wales, NSW 2052, Australia

<sup>3</sup>Graduate School of Chinese Academy of Sciences, Beijing 100049, China; qingxiaojin@gmail.com

Ida & Lin 2004; Chambers 2009). The measurement precisions that make the detection of such short-period exoplanets possible have over recent years continually improved for both Doppler (e.g. Gl 876 d (Rivera et al. 2005), Gl 581 c (Udry et al. 2007), 61 Vir b (Vogt et al. 2010)) and transit (e.g. Kepler-4b (Borucki et al. 2010)) detection. What then are the possible formation mechanisms that can produce such close-in terrestrial and super-terrestrial planets?

Several models have been proposed for the formation of close-in terrestrial planets. Raymond et al. (2006) have shown that super-Earths could form interior to a migrating Jovian planet. As they migrate inward, such gas-giants can shepherd planetary embryos interior to their orbits, which can then further collide and merge to generate Earth-like planets (Zhou et al. 2005). It has also been suggested that orbital migration and planet-planet scattering could potentially produce short-period super-Earths (Brunini & Cionco 2005; Terquem & Papaloizou 2007; Raymond et al. 2008). Whatever the mechanism for their formation, it is likely that such planets are common around at least low-mass stars (Kennedy & Kenyon 2008).

In all these scenarios, the formation of short-period Earth-like planets is associated with the migration of gas-giant planets. According to the core accretion paradigm for planetary formation, the isolation cores in the terrestrial planet formation region, and the solid cores of gas-giants, are both formed within  $\sim 1$  Myr from kilometer-sized planetesimals (Safronov 1969; Wetherill 1980). Subsequently massive solid cores accrete disk gas to form giant planets (Kokubo & Ida 2002; Ida & Lin 2004) at  $\sim 3-6$  Myr, before the disk disperses (Haisch et al. 2001). In the late stage of planet formation, when giant planets have ceased migration after the gas disk clears, the disk of countless planetesimals and planetary embryos will become turbulent due to stirring by gas-giants over hundreds of million years (or potentially even longer). In the meantime, it is expected that orbital crossings and giant impacts will frequently occur, which could lead to the formation of terrestrial planets (Chambers 2001; Raymond et al. 2004; Zhang & Ji 2009) and short-period Earth-like planets.

In this Letter, we present a potential new formation mechanism for short-period Earth-like planets in the late stage of planet formation through a collision-merger scenario. In this mechanism, a planetary embryo is directly kicked to a close-in orbit after a collision with another embryo, and then the larger merged body is seized by the central star as a hot Earth-like planet.

## 2. SIMULATION SETUP

Extrasolar planetary systems that harbor pairs of Jupiter-to-Saturn-mass companions are of particular interest to researchers (Gozdziewski 2002; Ji et al. 2005; Zhang et al. 2010), e.g., OGLE-06-109L bc (Gaudi et al. 2008), 47 Uma bc (Butler & Marcy 1996; Fischer et al. 2002), Gl 876 bc (Marcy et al. 2001). It is interesting to consider whether it is likely that such systems might host additional hot terrestrial planets (as, for example, the Gl 876 system does in the form of Gl 876 d – Rivera et al. (2005)), and further how such planets might form and evolve. We have therefore carried out simulations that explore such a system architecture.

In total, 30 runs were performed using a hybrid symplectic algorithm in the MERCURY package (Chambers 1999) for following two such systems. The initial conditions of the two systems simulated were:

**Simulation 1** - two giant planets are simulated with initial orbital parameters ( $M_P, a, e_p$ ) =  $(0.71 M_{\text{Jup}}, 2.3 \text{ AU}, 0.001)$  and  $(0.27 M_{\text{Jup}}, 4.6 \text{ AU}, 0.11)$ , to emulate the OGLE-2006-BLG-109L system (Gaudi et al. 2008). 500 planetary embryos and planetesimals<sup>1</sup> with total mass  $10 M_{\oplus}$  were distributed between  $0.3 \text{ AU} < a < 5.2 \text{ AU}$  and with  $e < 0.02$ . Each of the 26 runs carried out over 400 Myr.

**Simulation 2** - two giant planets are simulated with initial orbital parameters ( $M_P, a, e_p$ ) =  $(2.9 M_{\text{Jup}}, 2.08 \text{ AU}, 0.05)$  and  $(1.1 M_{\text{Jup}}, 3.97 \text{ AU}, 0.001)$ , to emulate the 47 Uma system (Fischer et al. 2002). 648 planetary objects with total mass of  $5.14 M_{\oplus}$  were distributed in the region  $0.3 \text{ AU} < a < 1.6 \text{ AU}$  with  $e < 0.02$ . Each of the four runs evolved over 100 Myr.

The other initial orbital elements of each planetary embryo (or planetesimal) are randomly generated – the arguments of periastron, longitudes of the ascending node, and mean anomalies range from  $0^\circ$  to  $360^\circ$ , and inclinations are from  $0^\circ$  to  $1^\circ$ . In addition, the hybrid integrator parameters are adopted as a stepsize of 3 days ( $\sim$  a twentieth of a period for the innermost possible body at 0.3 AU), and a Bulirsch-Stoer tolerance of  $10^{-12}$ . At the end of integration, the changes of energy and angular momenta are  $10^{-3}$  and  $10^{-11}$ , respectively. In these runs, the gravitational interactions of all bodies are taken into account. Two bodies are assumed to collide whenever the distance between them is less than the sum of their physical radii (Chambers 1999). If two objects collide, they are merged into a single body, without fragmentation, after the collision.

---

<sup>1</sup>Herein the masses of embryos range from several lunar-mass to Mar-mass, and those of smaller "planetesimals" have approximately a lunar mass, rather than a planetesimal mass.

### 3. RESULTS

#### 3.1. Simulation results

In our simulations, we find that the collision-merger mechanism produces close-in terrestrial planets in 20% of the runs carried out (5 of 26 **Simulation 1** runs, and 1 of 4 **Simulation 2** runs). The simulations exhibit a classical planetary accretion scenario in their late stage formation (Chambers 2001; Raymond et al. 2004). Figure 1 shows snapshots at various evolution times for a representative run of **Simulation 1**. Initially, the embryos and planetesimals reside in a cold disk, which is quickly stirred by the two gas-giants and excited to highly eccentric orbits within 0.1 Myr. We also see that three small bodies are involved in a 1:1 resonance with the inner giant by that time. By the end of 1 Myr, most of the initial objects have been removed by ejection or collision due to frequent orbital crossings in this chaotic stage. In addition, we see that a close-in planet has formed at  $\sim 1$  Myr which subsequently remains very stable. At the conclusion of the run (400 Myr), three planetesimals survive, of which one has been seized as a Trojan body by the inner giant, and the other two move at  $\sim 1$  AU in eccentric orbits.

Figure 2 shows the time evolution of the mass, semi-major axis, and eccentricity of the short-period terrestrial planet formed in the **Simulation 1** run shown in Fig. 1. At 0.0356 Myr, two bodies that may be excited by secular resonance of gas-giants, collide at very high eccentricities ( $e = 0.91$  and  $0.80$ , shown by the red and black lines in Fig. 2, respectively) and are then assumed to merge into a single planetary embryo. That merged body (the remaining black line in Fig. 2) is captured by the parent star as a short-period planet, and its orbit dramatically shrinks from  $\sim 0.4$  AU at the time of the collision, down to 0.077 AU. Subsequently, three additional collisions take place over the further late-stage evolution of that merged object. Fig. 2 shows that the embryo moves slightly inward at each collision, and that its mass also increases. Moreover, we note that it finally becomes a 3.3 Mercury-mass planet with a close-in orbit about 0.056 AU, and its eccentricity drops down to  $e=0.13$  after the last collision. The orbit may then, of course, be further circularized by tidal interaction with the star over even longer timescales.

Figure 3 shows the formation and evolution of a similar terrestrial planet that emerges in one of the runs for **Simulation 2**. At 2.2 Myr, the semi-major axis of a  $\sim 0.9$  Mercury-mass embryo drops down from  $\sim 0.8$  AU to 0.06 AU as a result of a collision with a highly-eccentric planetesimal excited more than a million years earlier. The merged body has an eccentricity that drops from 0.90 to 0.50 immediately after the impact. The enlarged, merged body subsequently undergoes additional collisions, and its eccentricity further evolves to  $e=0.33$  (after its last collision) with a final mass of 1.3 Mercury-mass. Here, the collision-merger

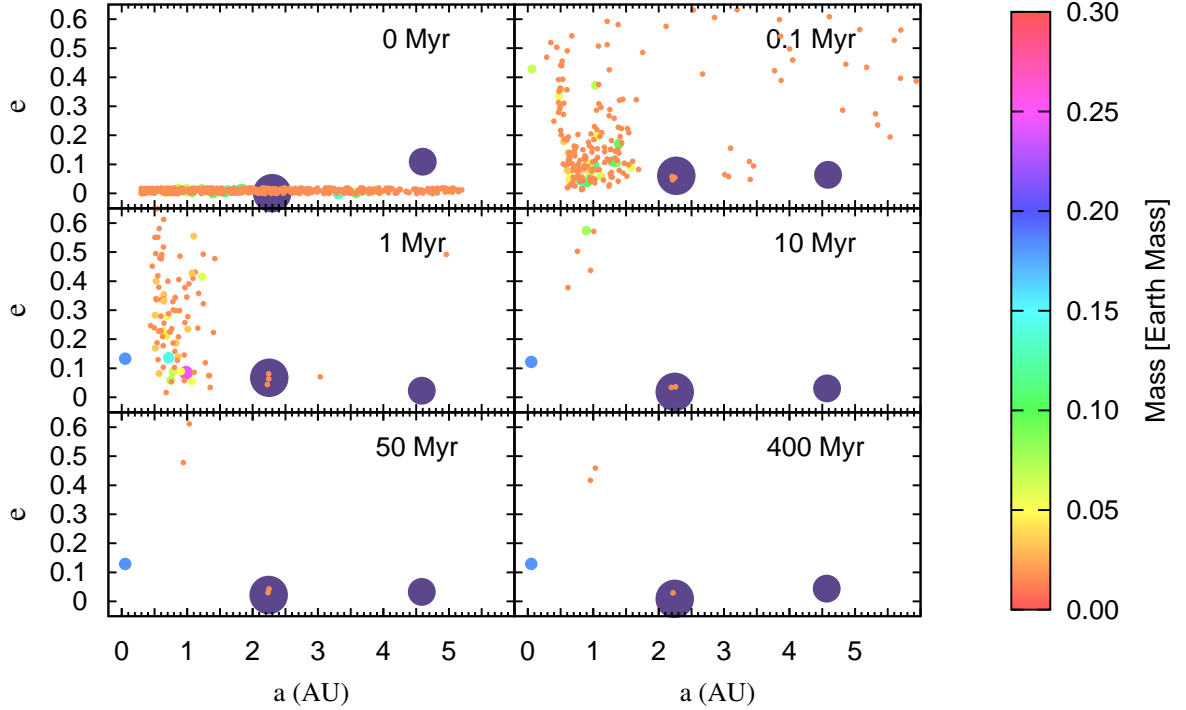


Fig. 1.— A snapshot of planet formation in the late stage for **Simulation 1**. The panels show the orbital eccentricity versus semi-major axis for each surviving body at simulation times of 0, 0.1, 1.0, 10, 50 & 400 Myr. The radii and the color of the embryos and planetesimals are related to their mass, with radius proportional to  $m^{1/3}$ . The two giants are, respectively, at 2.3 and 4.6 AU. A close-in terrestrial planet forms at  $\sim 1$  Myr and it remains stable over secular evolution.

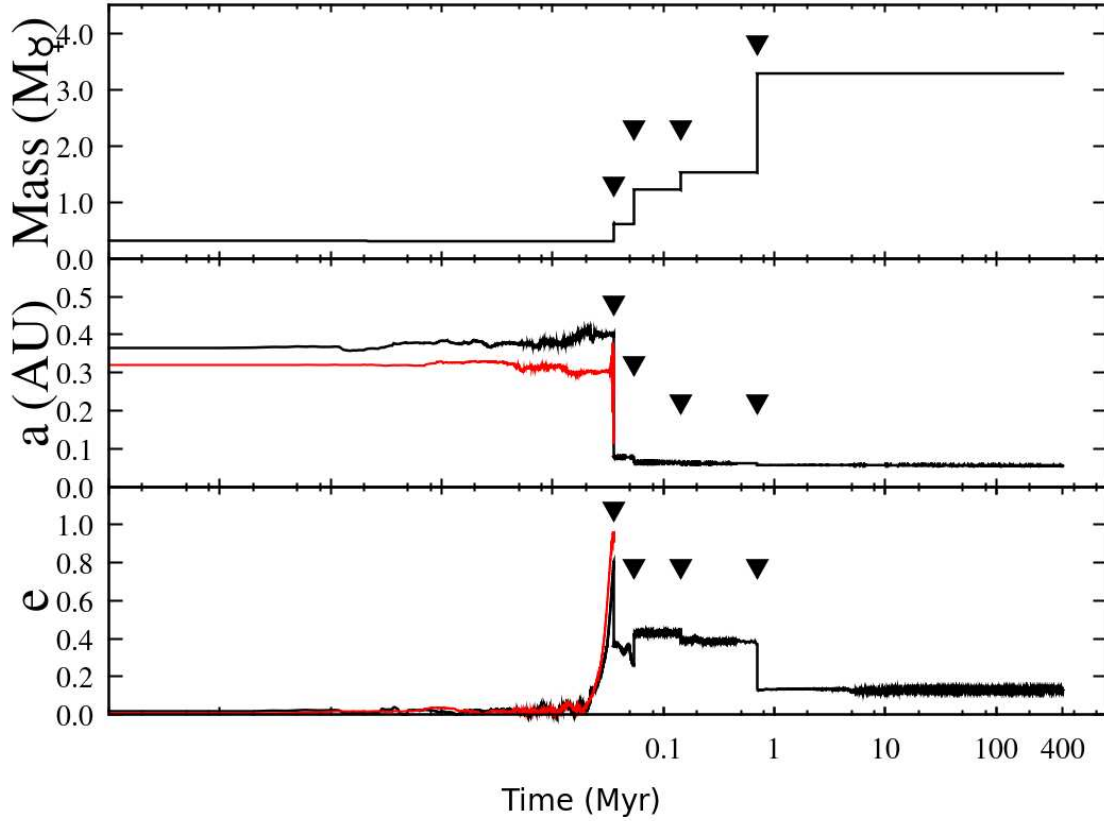


Fig. 2.— Mass, semi-major axis and eccentricity evolution of the short-period terrestrial planet the emerges from the **Simulation 1** run shown in Fig. 1. The black and red lines in the lower two panels show the semi-major axis and eccentricity evolution of the two bodies that collide to form a merged planetary embryo, which is kicked from 0.4 AU to 0.077 AU at 0.0356 Myr. Subsequently that merged embryo (shown as a single black line after 0.0356 Myr) is subject to further collision-mergers, with the epoch of each collision shown by the *solid triangles*. The resultant mass evolution of this body is shown in the upper panel.

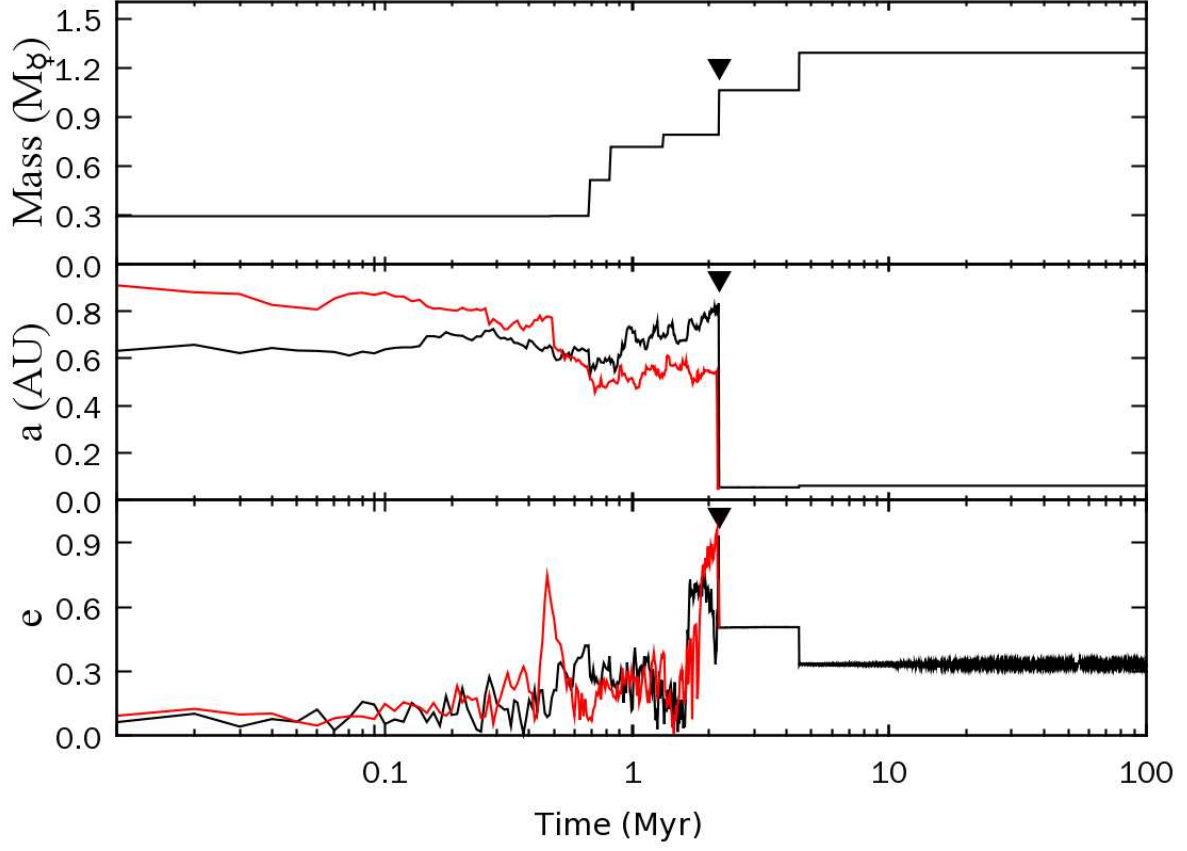


Fig. 3.— Mass, semi-major axis and eccentricity evolution of a short-period terrestrial planet that emerges from a run of **Simulation 2** – layout is the same as for Fig. 2. In this case the first collision-merger event occurs at 2.2 Myr, and the embryo is thrown from its location of  $\sim 0.8$  AU at the time of the collision to 0.06 AU.

scenario may provide some clues of the origins of the moderate eccentricities seen in super-Earths detected to date (e.g., HD 181433 b (Bouchy et al. 2009)).

The major difference in the evolution of these two examples is that the short-period planet that evolved in **Simulation 1** was moved into an inner orbit at a very early stage, and subsequently accreted a majority of the mass available in nearby orbits; while the **Simulation 2** planet had almost completed accretion into a Mercury-mass embryo before it moved closer to the star. In all simulations, we notice that terrestrial planets and bodies formed at short periods via collision-merger events come into being within 10-30 Myr, which agrees with the estimated timescale of terrestrial core formation (Yin et al. 2002), as derived from the chronometry of meteorites and numerical simulations of terrestrial planet formation (Chambers 2001; Raymond et al. 2004; Zhang & Ji 2009). In addition, we find that all survivors remain stable in their final configurations.

These results indicate that a collision-merger mechanism could indeed produce short-period, terrestrial planets in two systems that host two gas-giants. Similarly, we also find the above outcomes in other 4 runs. However, a natural question then arises – do the bodies that take part in these collisions really merge? Or will they become fragmented?

### 3.2. Merger versus fragmentation

In the accretion model of MERCURY, a collision-merger scenario occurs whenever the distance between two bodies is less than the sum of their physical radii (Chambers 1999), and the package models the two bodies merging inelastically to form a single new body that conserves mass and total momentum. The collisions in the runs, therefore, are considered to be perfect gravitational aggregations, which assumes that enough energy is dissipated in the collision for the two bodies to remain gravitationally bound. However, actual collisions could have a result that ranges anywhere from this result (complete merger), through partial fragmentation, to the complete shattering and disintegration of both impactors. (Wetherill & Stewart 1993).

Whether these bodies either fragment or cohere in a collision will obviously depend on the – currently poorly understood – physical properties of the colliding bodies (Wetherill 1980). What can be said is that the outcome will be extremely complicated. To assess the likely state of the merger vs fragmentation for two bodies in a collision, we can, though, make order-of-magnitude estimates.

Consider two bodies of the same mass  $m$ , with relative velocity at infinity  $\sigma$ , and the sum of the physical radii  $R_s$ . The collision velocity for a head-on collision between them is



(Safronov 1969; Wetherill 1980; Armitage 2007),

$$v_c = (\sigma^2 + v_{esc}^2)^{1/2} \quad (1)$$

where  $v_{esc} = \sqrt{4Gm/R_s}$  is the escape velocity at the point of collision, a parameter used to evaluate whether they will physically collide. Take the coefficient of restitution as  $\epsilon$ , then accretion will result if  $\epsilon v_c < v_{esc}$ , even if the initial impact results in fragmentation into two bodies. Conversely, the bodies will be unbound if  $\epsilon v_c > v_{esc}$ . Thus, the threshold value of the coefficient of restitution for these outcomes is (Armitage 2007),

$$\epsilon = \left(1 + \frac{\sigma^2}{v_{esc}^2}\right)^{-1/2} \quad (2)$$

This shows that if  $\sigma \ll v_{esc}$ , merger and growth is likely unless collision is totally elastic; whereas  $\sigma \gg v_{esc}$  leads to fragmentation.

For the **Simulation 1** run shown in Fig. 2, we have used the above equations to assess the outcome of the first collision as it happens between two identical Mercury-like embryos, which allows us to make a rough evaluation of the likely outcome by calculating the instantaneous velocities of the impactors at the epoch just before the collision. Now we notice that at the first collision the body was impacted onto a close-in orbit. The  $v_{esc}$  of the two impactors are nearly the same –  $3.12 \text{ km s}^{-1}$  (assuming equal bulk density); the velocities of the impactors at the collision epoch near the pericenter are estimated to be  $43.21 \text{ km s}^{-1}$  and  $35.50 \text{ km s}^{-1}$ , respectively, thus we have an approximate relative velocity projected to the relative position of two colliding bodies of  $13.49 \text{ km s}^{-1}$ . In this case, a merger requires  $\epsilon \leq 0.23$ , which is close to the accretion condition ( $\epsilon \leq 0.34$ ) in realistic accretion model for head-on collision (Kokubo & Genda 2010). On the basis of above analysis, a merger seem to be possible for two eccentric objects when the collision occurs in the nearby region of central star, subsequently the merged body is seized by the star at close-in orbit. In the collision-merger process, moderate energy should be released, and they could be converted into the internal heat of the merger in the collision between embryos, e.g., simulations of a supposed Moon-forming impact show that the collision can deliver prodigious energy to the Earth, which could lead the proto-Earth to a mixed solid-melt state (Canup 2008).<sup>2</sup>

We also obtain similar results for the **Simulation 2** run shown in Fig. 3. In addition, Leinhardt & Richardson (2002) showed that a large mass ratio between two impactors will tend to lead to merger and aggregation – the accretion probability is  $\sim 60\%$  (averaged over

---

<sup>2</sup>At the very time before/after the collision, the fractional energy change due to integrator was about 9 part in  $10^4$ . Additional energy loss may arise from the ejection of other embryos or transfer to the envelope and core of giant planets (Li et al. 2010).

all impact parameters) for average mass ratio of 1:5. This suggests that the first collision seen in this run, where the mass ratio of 1:3.43, is likely to result in a merger.

#### 4. DISCUSSION and CONCLUSION

We have uncovered a new mechanism for producing short-period terrestrial planets via collisions-mergers in the late stages of planetary formation. In this mechanism, two highly-eccentric bodies first undergo a severe orbital crossing and then form a short-period planet via collision-merger. In the set of simulations performed to date, this mechanism produces a short-period, terrestrial planet in 20% of runs.

As mentioned previously, the formation rate for short-period terrestrial planets via a collision-merger process is only a moderate 20%. However, this low rate may be a result of the limits imposed on our simulations by current computational capabilities, which restrict our adopted population of embryos and planetesimals to a few hundred objects with a total mass of only several times that of the Earth. The resultant planetesimal disk in our simulations is much smaller than that of the Minimum Mass Solar Nebula ( $\sim 0.01 M_{\odot}$  within 30 AU (Weidenschilling 1977; Hayashi 1981)) – which would also contain billions of small bodies. Increasing the number of bodies and the total mass of the proto-planetary disk would likely increase the efficiency with which this mechanism produces short-period terrestrial planets.

In addition, it is worth noting that close-in planets emerge from our simulations within a few million years. This is a significantly shorter timescale than the billion years over which the Solar System is thought to have undergone significant evolution. So, while near-infrared observations of young cluster samples, indicate an overall dust disk lifetime of  $\sim 6$  Myr (Haisch et al. 2001), the planetary system will actually continue to evolve over much longer timescales following the clearing of the dust and gas disk. During this late stage of planetary formation, frequent orbital crossings and huge impacts will occur, which are likely to significantly boost the feasibility of collision-merger events producing short-period terrestrial bodies.

The collision-merger scenario for the formation of short-period planets does not require perfect accretion. Rather it relies on the collisions pushing the resultant body inward, so that the central star can capture it as a short-period planet. In this sense, such a mechanism could play a key role in throwing the largest fragments resulting from severe impacts into short-period orbits. On the other hand, given the diversity in the architectures of currently known systems, exoplanets are likely to form through a variety of mechanisms rather than through a uniform dominant process (D. Lin 2009, private communication). Our simulation

results show one potential mechanism for the origin of short-period terrestrial planets in a compact disk with two gas-giants, and may predict an abundance of close-in bodies for this family.

We thank the anonymous referee for useful comments and suggestions that helped to improve the contents. We also thank J.E. Chambers, D.N.C. Lin and E. Kokubo for informative discussions and insightful comments. J.H.J. is very grateful to the Australian Academy of Sciences for the support of his stay at UNSW, and to Chris Tinney and UNSW Astrophysics Department for their hospitality. This work is financially supported by the National Natural Science Foundation of China (Grants 10973044, 10833001, 10573040, 10673006, 10233020), the Natural Science Foundation of Jiangsu Province, and the Foundation of Minor Planets of Purple Mountain Observatory.

## REFERENCES

- Armitage, P. J. 2007, Lecture Notes on the Formation and Early Evolution of Planetary Systems, [astro-ph:0701485]
- Borucki, W. J., et al. 2010, *Science*, 327, 977
- Bouchy, F., et al. 2009, *A&A*, 496, 527
- Brunini, A., & Cionco, R. G. 2005, *Icarus*, 177, 264
- Butler, R. P. & Marcy, G. W. 1996, *ApJ*, 464, L153
- Canup, R. M. 2008. *Phil. Trans. R. Soc. A*, 366, 4061
- Chambers, J. E. 1999, *MNRAS*, 304, 793
- Chambers, J. E. 2001, *Icarus* 152, 205
- Chambers, J. E. 2009, *Annual Review of Earth and Planetary Sciences*, 37, 321
- Fischer, D. A., et al. 2002, *ApJ*, 564, 1028
- Gaudi, B. S., et al. 2008, *Science*, 319, 927
- Gozdziewski, K. 2002, *A&A*, 393, 997
- Haisch, K. E., Jr., et al. 2001, *ApJ*, 553, L153

- Hayashi, C. 1981, Progress of Theoretical Physics Suppl., 70, 35
- Ji, J. H., Liu, L., Kinoshita, H., & Li, G.Y. 2005, ApJ, 631, 1191
- Kennedy, G. M., & Kenyon, S. J. 2008, ApJ, 682,1264
- Kokubo, E., & Ida, S. 2002, ApJ, 581, 666
- Kokubo, E., & Genda, H. 2010, ApJ, 714, L21
- Ida, S., & Lin, D.N.C. 2004, ApJ, 604, 388
- Leinhardt, Z. M., & Richardson, D. C. 2002, Icarus, 159,306
- Li, S. L., Agnor, C. B., & Lin, D. N. C. 2010, ApJ, 720, 1161
- Lin, D. N. C., et al. 1996, Nature, 380,606
- Marcy, G. W., et al. 2001, ApJ, 556, 296
- Mayor, M., & Queloz, D. 1995, Nature, 378, 355
- Raymond S. N., Quinn T., Lunine J. I., 2004, Icarus, 168, 1
- Raymond, S. N., et al. 2006, Science, 313, 1413
- Raymond, S. N., et al. 2008, MNRAS, 384, 663
- Rivera, E. J., et al. 2005, ApJ, 634, 625
- Safronov,V.S. 1969, Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets (Moscow:Nauka)
- Terquem, C., & Papaloizou, J. C. B. 2007, ApJ, 654,1110
- Udry, S., et al. 2007, A&A, 469, L43
- Vogt, S. S., et al. 2010, ApJ, 708, 1366
- Weidenschilling, S. J. 1977, MNRAS, 180,57
- Weidenschilling, S. J., & Marzari, F. 1996, Nature, 384,619
- Wetherill, G. W. 1980, ARA&A, 18, 77
- Wetherill, G. W., & Stewart, G.R. 1993, Icarus, 106, 190

Yin, Q., et al. 2002, *Nature*, 418, 949

Zhang, N., & Ji, J. H. 2009, *Science in China Series G* , 52(5), 794

Zhang, N., Ji, J. H., & Sun, Z. 2010, *MNRAS*, 405, 2016

Zhou, J.-L., Aarseth, S. J., et al. 2005, *ApJ*, 631,L85